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DEVELOPING A STANDARDISED APPROACH TO MEASURING THE ENVIRONMENTAL FOOTPRINT OF ANTARCTIC RESEARCH STATIONS

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Within the Antarctic Treaty Consultative Meetings, momentum has been building to define and manage the human footprint of research stations in Antarctica. This has been reflected by national operators and researchers offering varied approaches to measuring “footprint”. By not having a standard method, comparative measurements have shown great disparity. By formulating a standard approach, this study delivered a method that enables comparison. To achieve this, recognition was needed of the vastly different environments in which Antarctic stations are situated. To aid this, defining what to measure, resources consumed, and location descriptors were developed to represent the actual impact of the footprint. The model was then tested on Australia’s Davis Station. Inspection of aerial photography and mapping with geographical information systems was supported by field measurements. The model was found to be applicable, with on-the-ground measurements detecting additional footprint area not obvious from the desktop methods. While open to refinement, this study offers a standardised and comparable approach to measuring the footprint of Antarctic research stations.

Keywords: Antarctica; footprint; environmental impacts; research stations.

Introduction

Environmental impact assessments focus inherently upon new projects and remediating the negative impacts of prior activities. Assessing the environmental impacts of existing infrastructure is generally not considered yet there is relevance to understanding existing impacts as they provide a portrait of the ongoing and cumulative toll on the environment. Within the Antarctic Treaty Consultative Meetings, measuring and assessing these impacts, particularly for the research stations, has been gaining momentum under the broad title of "footprint". How and what to measure has been an area of debate with many different methods and approaches taken, resulting in incomparable results (for example: GERG, 2003; DFAT & DEH, 2005; CAA, 2008; Klein *et al.*, 2008). To address the problem of the inconsistent application/measurement of footprint, this study aimed to create a method of measuring the footprint of any Antarctic research base incorporating site-specific features to produce a quantifiable and comparable result. By applying such a formula to a station, an appreciation and understanding of the overall environmental impact would also be possible.

The theme of human footprint has been raised recurringly within the Antarctic Treaty System (ATS) meetings, reflecting acknowledgment of the concept by Treaty Parties. In a summary paper presented by Australia to the 2010 Antarctic Treaty Consultative Meeting, it was reported that 51 information and working papers had mentioned "footprint" between 1998 and 2010 (Secretariat of the Antarctic Treaty, 2010). This momentum has continued with two papers presented in 2011 (Secretariat of the Antarctic Treaty, 2011; ASOC, 2011) specifically dedicated to footprint, and discussions within the Committee for Environmental Protection at the 2011 meetings. This included a general interest in development of the terminology of footprint. A strict definition of how footprint relates to Antarctica, however, appears to vary; Australia's delegation highlighted that it should be practically applicable, whereas Argentina preferred "a general approach rather than a specific definition" (ATS, 2011). Australia's desire for a practicably applicable "footprint" definition provided the impetus for this study.

Within Antarctic policy, mentions of defining and measuring the footprint of activities and facilities have been increasing exponentially since the Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol) entered into force in 1998. The momentum behind this interest in footprint as an environmental pressure is unlikely to subside. The foreseeable outcome for footprint within the Antarctic sphere is for it to gain broader recognition as a genuine environmental measure to improve planning, assess environmental impacts and provide for awareness of inviolate areas of Antarctica. Although the model produced by this study was designed for the national stations, it could potentially be adapted for assessment of research projects, camps, and new infrastructure. The approach of this model could also be utilised to manage and assess facilities and projects in wilderness and sensitive environments outside Antarctica. This could include facilities throughout the latitudes, such as within protected wilderness areas, slowly-regenerating alpine environments and the Arctic.

Knowledge of the footprint of Antarctic stations also provides a valuable tool for the policy and decision-makers that make their choices remote from the locations actually experiencing the consequences. It also enables an understanding of the environmental impact that the human presence has on the continent for the vast majority of people who will never have the opportunity to witness it first-hand.

Many different definitions of the term "footprint", regarding human interactions within Antarctica have been used (for example: Sanderson *et al.*, 2002; Klein *et al.*, 2008; Hughes *et al.*, 2011). In this study, footprint was defined as "the ground surface area that is tangibly modified, disturbed or impacted by the presence of an Antarctic research station and its associated support and logistical activities". Even with this given definition of footprint, there is still a wide arc of potential measurements that might be included. To limit these, the most important factors considered were the area of buildings, disturbed ground, out-features (such as field huts and runways), station and resource usage, and the specific characteristics of a given station environment.

Quantifying this definition of footprint, especially in Antarctica, is largely novel, and prior approaches have been location-specific. The most thorough analysis of this definition of environmental impact footprint of an Antarctic station found throughout the literature review process is an independent report and associated papers on the USAP's McMurdo Station (Klein *et al.*, 2008; GERG, 2003; Kennicutt II *et al.*, 1999). To establish the footprint of McMurdo Station, these studies relied on aerial photography (Kennicutt II *et al.*, 1999). The benefits of this approach to finding the station's footprint was that it was relatively simple, a quantifiable area could be derived from the analysis, it didn't require pre-existing detailed maps, and it could be assessed with a historical perspective by accessing archival photography. The foreseeable disadvantages of this method in contrast to the model produced by this study is that it had a lower precision (most Antarctic stations are dwarfed in comparison to McMurdo) and it relied on being able to delineate disturbed and undisturbed surfaces from photography making it difficult to translate to use for stations in snow and ice covered environments. The problem with location-specific methods such as this is that they make cross comparison and data sharing difficult — the latter of which is an inherent component of the Antarctic Treaty. This lack of uniformity in approach to station footprint has also led to publications of results that drastically differ.

In 2006 the Australian Government's environmental department included the Australian Antarctic Territory, for the first time, within its five-yearly State of the

Environment (SoE) Report. Included in this report as Indicator 65, was "station footprint" (AAD, 2008a). This footprint was calculated by extracting measurements from existing geographical information system data (GIS) for Australia's stations (D. Smith, pers. comm. 18/7/08). This method used an engineer's definition of footprint — "the area of ground taken up by a building" — not including any potential spread of disturbance. Further, comparison of the GIS data used with aerial photography, as well as expert advice (M. Pekin, pers. comm. 24/9/08), revealed that the area measured (such as roads) did not accurately represent the true on-the-ground features. Although this method would allow for a comparison of measurements if a similar GIS data set were developed for all Antarctic stations, it would not accurately reflect the on-the-ground footprint or its significance.

To develop and verify this study's method of footprint measurement it needed to be practically tested. Australia's Davis Station was selected for the initial application of the method because of multiple factors. Firstly, accessibility to, and support by, the Australian Antarctic Division (AAD) provided sufficient data and staff expertise. Of the Australian Antarctic stations, Davis also provided the best subject, as it represented a universal station without any extremely unique features. As the opportunity was presented, the footprint parameters were also tested at Australia's Casey Station.

With the difficulty of access to Antarctica, utilising geographical information systems (GIS) and remote sensing provided ready assessment of Davis's footprint with considerable accuracy. These systems allowed for geographical delineation of the footprint, as well as precise calculation of its area. Ground-truthing on location was also conducted to test the accuracy of the initial footprint measurement provided by the GIS.

In addition to the visibly obvious footprint of buildings and disturbed land at Antarctic stations, there was also an expected impact upon the environment from the initial construction and presence of these facilities that may not be readily evident. To include this portion of the footprint, an assumed disturbance buffer area was applied. This allowed consideration of the disturbance during construction, personnel movement around buildings, the object's purpose, and environmental effects such as snowdrift accumulation, wind channelling, and altered ground hydrology.

Some Antarctic stations have rock-founded runways. Although they provide advances in logistical capabilities and emergency management, their footprint upon the Antarctic environment cannot be ignored. The significant impact upon the environment and wildlife caused by the construction of such runways has been established (for example: Micol and Jouventin, 2001). Within this footprint model, runways should be assessed equally to roads and associated heavily disturbed levelled areas. Likewise, associated aerodrome structures should be assessed as station buildings. Runways should be included equally within a station's location descriptors. In reporting, a national operator could delineate the footprint of the runway from other modified surfaces to explain the significantly additional area and to take into account that these facilities are often shared. Field huts are also an important consideration, although taking into account their often transient construction and low visitation is essential.

To add context to a footprint measurement, data of the resource requirements and environmental loads of stations were included within the measurement. These figures included fuel and water consumption and wastewater production. Inclusion of this data by usage (compared to storage capacity or similar) provided consideration of the continual cartage and storage requirements and the potential risk from the turnover of such quantities. The inclusion of this data, accessible from many national Antarctic programs, added valuable indicators that portray a station's environmental demands and thus affects its footprint. In isolation this data is of limited use but including the information within the footprint formula added a useful and easy tool for comparison of operational efficiency and loadings between stations. To enable this data to be comparable, it was calculated as a standardised index of per person or per person per day. This standardised index allowed an accurate depiction regardless of the fluctuation between, and within, station populations. It would also represent efficiencies that may be gained by populous stations.

Categorising station location characteristics was considered an essential feature for inclusion in the development of a practical footprint measurement. Categorisation is the separation of the footprint measurement according to a station's features (location descriptors) to represent comparatively the real-world impact that they have. On a macro-scale, stations that are established on ice sheets and shelves are considered to have less of a physical environmental impact than those in coastal ice-free rock and gravel areas (Benninghoff and Bonner, 1985). Similarly on a micro-scale, biological communities within coastal ice-free locations are not evenly spread, with some stations located in biological diverse areas and others in near-sterile sites. Simply comparing station footprints without taking into account such location-specific factors would produce a measurement of limited application. A station's building method was also included as this is closely linked to its location as well as its operator's intentions. Field refuges were deliberately excluded from this part of the assessment (with the exception of building methods) as they are often intentionally positioned within close proximity to areas of scientific value.

Methods

The majority of spatial analysis for the station footprint was developed using GIS. This involved using the Australian Antarctic Data Centre's (AADC) map data, and applying additional layers (for the heavily modified surfaces and the disturbance buffer) developed for this study. This was done using a PC operating Microsoft Windows XP® with the software ESRI ArcGIS® 9 ArcMap 9.2. The areas of all features contributing to the environmental impact footprint of the test case station were calculated in the ArcMap software. The majority of spatial data was sourced from photogrammetry of aerial photography. This method had an accuracy of 0.1 m. All mapping was done in a Lambert Azimuthal equal-area projection with a central meridian and true scale — replicating the same format used by the SoE indicator.

To accurately represent the on-the-ground environmental impact comprising a footprint, multiple tiers of intensity and activity are inherent. These were divided into heavy, moderate, and lightly modified surfaces. Heavy and moderate intensity disturbance was confined to the significantly modified environments of stations. This would usually be restricted to the core station operational area and significant outlying infrastructure including remnant landfill sites, rock quarries, roads and scientific infrastructure. Heavy modification was defined as natural surfaces that were disturbed and compacted to a similar extent to roads and other levelled areas. Moderate modification was defined as surfaces that are regularly and significantly disturbed, such as areas where spoil from road clearing is deposited. Lightly modified surfaces are the broadest scale of the footprint as they extend out to include the entire disturbance created by field studies, access routes, and field refuges (Kiernan and McConnell, 2001). Although of minimal impact these factors do have a light physical disturbance and therefore are part of the station's footprint. For this study, mapping was constrained to heavily modified surfaces, which was accessed from recent aerial photography, and then ground-truthed during a field study.

To calculate the assumed disturbance area around station facilities a buffer area was applied. This was developed with discussion and agreement with engineers, expeditioners and other experienced Antarctic staff (for example: M. Pekin, pers. comm. 24/9/08; V. Morgan, pers. comm. 27/11/08). Resulting from these discussions, a buffer of 10 metres was applied around major structures (including all buildings, tall and solid structures), five metres around lesser structures (permeable features such as stilts and frames, field refuges) and one metre around the least interfering features (low lying and low resistance features such as poles and fences) (Table 1). Mapping and measuring the buffer footprint area was achieved by using ArcMap GIS software to apply it to the station infrastructure.

Table 1. The locations of disturbance buffer testing at field study sites.

Disturbance Buffer Samples							
Station	Building	Bldg Section	Orientation	Buffer (m)	Actual (m)	Accuracy	Description
Casey	Science	NW	W	10	10	Correct	
	Science	NW	N	10	10	Correct	
	WWTP	NE	N	10	12	Exceed	Includes Road
	WWTP	NE	E	13	26*	Exceed	Unmarked storage area
	WWTP	SE	E	16	45*	Exceed	Unmarked storage area
	Theodolite Shelter	NW	N	10	10	Correct	
	Theodolite Shelter	SW	S	10	10	Correct	
	Balloon Release	W	W	10	30+	Exceed	
	Balloon Release	S	S	10	10	Correct	
	RMB2	S	S	10	10	Correct	
	RMB2	E	E	10	10	Correct	
	Tank House	SE	S	10	10	Correct	
	Tank House	SE	E	10	10	Correct	
	Red Shed	S	S	10	10*	Correct*	Snow concealing further disturbance
	Wind Turbine	NE	NE	—	13.5	—	No previous buffer applied
	Wind Turbine	SE	SE	—	13.5	—	No previous buffer applied
	Wind Turbine	SW	SW	—	13.5	—	No previous buffer applied

Table 1. (*Continued*)

Disturbance Buffer Samples							
Station	Building	Bldg Section	Orientation	Buffer (m)	Actual (m)	Accuracy	Description
	Wind Turbine	NW	NW	—	13.5	—	No previous buffer applied
	Helipad	N	N	5	12.5	Exceed	
	Piping near ANARESAT	W	W	5	1	Under	
	Piping near ANARESAT	E	E	5	1	Under	
	Old Carpenters Workshop	NNW	NNW	10	3	Under	Old style building, restricted by boulders
	Old Carpenters Workshop	SSW	SSW	10	4	Under	As Above
	Summary: 10 buffer accurate (53%), 5 in excess (26%), 4 over estimated (21%)						
Davis	Balloon Release	SW	NW	10	10	Correct	
	Balloon Release	N	NW	10	14	Exceed	
	Field Store	N	NW	10	16	Exceed	
	Field Store	N	NE	10	16	Exceed	
	Walkway	NE	NE	—	1		No previous buffer applied
	Walkway	SW	SW	—	2		No previous buffer applied
	EVS	S	SW	10	12	Exceed	
	EVS	S	SE	10	12	Exceed	
	Road To Helipad	NE	NW	1	6	Exceed	Road 6 m wide
	Road To Helipad	NE	SE	1	6	Exceed	Road 6 m wide

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Table 1. (*Continued*)

Disturbance Buffer Samples							
Station	Building	Bldg Section	Orientation	Buffer (m)	Actual (m)	Accuracy	Description
	Operations Building	W	NW	10	13	Exceed	
	Operations Building	W	SW	10	12	Exceed	
	Operations Building	S	SW	10	13	Exceed	
	Operations Building	S	SE	10	34*	Exceed	Unmarked storage area
	Road to Marchins Landing	SW	NW	1	2	Exceed	
	Road to Marchins Landing	SW	SE	1	2	Exceed	
	Summary: 1 buffer accurate (7%), 13 in excess (93%), none over estimated.						

Data for the footprint were retrieved from a variety of sources. Station operational data (such as populations, water and fuel usage) were accessed from the AADC's SoE indicator reports (AAD, 2008a). Additional data not accessible from these sources, such as information on Davis Station's field huts, were compiled from various sources. Further information on station characteristics was also obtained while conducting the field study at the stations. The data required for the huts were compiled from AAD Engineering asset maps, the AAD Field Manual 2007, the AAD website (AAD, 2008b), and assorted AAD photography (iMage Antarctica, 2008). Communication with AAD staff also provided valuable information (e.g. T. Maggs, pers. comm. 13/3/08; B. Jones, pers. comm. 2/10/08). Measurements for the custom field huts had to be estimated by experienced AAD staff, and from existing photography (iMage Antarctica, 2008), as no official record of the dimensions were known.

Adding location descriptors to a station footprint adds a degree of qualitative measurement to an essentially quantitative assessment. The characteristics should reflect the station's environment in a pre-disturbance state, or be based upon nearby equivalent background sites. This enables the most specific, robust method to identify a station's true environmental footprint. The four location descriptor categorisations created were a station's *location*, *biological significance*, *geological significance*, and *method of building construction*. Inclusion of external or peer assessment by a relevant expert for a station's placement would also be required for non-biased categorisation.

Each of the 10 characteristics for all four location descriptors is novel and was designed by this study. Each location descriptor was produced by a desktop study of the possible characteristics of Antarctic stations. Included in the assessment was a literature review of the various environments inhabited by stations, past and present, and consultation with experienced Antarctic staff and researchers (e.g. T. Maggs, pers. comm. 25/8/08; M. Pekin, pers. comm. 24/9/08; B. Jones, pers. comm. 2/10/08; P. Quilty, pers. comm. 17/10/08; V. Morgan, pers. comm. 27/11/08; J. Gibson, pers. comm. 3/2/09). The resulting 10 categories (Table 2) in each of the location descriptors encompass a range of possible scenarios in Antarctica, but are not intended to be unequivocal or without amendment.

In addition to the theoretical method of measuring a station's environmental footprint there will always be station-specific peculiarities. The format and availability of data from individual stations and national operators will also be subject to broad variance. This availability and form of data will dictate the approach to data collection at each station for measuring its environmental impact footprint.

Modelling the test case's footprint required data on many aspects of the station. Data required included geometry of all structures and roads, heavily disturbed areas, station population figures and fuel and water usage. Measurements were obtained during a field study at Davis and Casey in December 2008, from pre-existing AAD data, and expert knowledge. The majority of spatial information was sourced from the Australian Antarctic Data Centre's (AADC) records. As the station is continually being modified, a cut-off date for data on the station facilities was set at 29 July 2008. Field measurements for the test case stations were obtained at Casey on 1–04, and at Davis 11–12 December 2008. During the field

Table 2. The station location descriptors.

Station Construction
1. On ice, fully removable, ski footings or similar, all waste products removed.
2. Footings irretrievable from ice.
3. Wastewater left *in situ*.
4. Any station infrastructure in ice-free areas.
5. Ice-free area, fully removable footings, guy wire anchored only.
6. Buildings irretrievable from ice.
7. Significant rock anchoring.
8. On site foundations.
9. Significant non-remediable alterations to geomorphology.
10. Permanent alterations, exposed rock, virtually irremovable.
Station Location
1. On ice, polar plateau, air resupply.
2. Within 50 km of coast.
3. Inland ice-free (such as nunataks, not dry valleys).
4. Inland traverse resupply over 100 km.
5. Coastal ice-free, or inland traverse route covering over 1 km of ice-free terrain.
6. On Antarctic Peninsula, or significant nesting/moulting areas within 1 km.
7. Area of significant scientific value.
8. Over 1000 tourist landings/season, or Peninsula within 100 km of another station.
9. Antarctic Peninsula within 10 km of another station.
10. Significant nesting/moulting site, or dry valley.
Geological Significance
1. Polar plateau ice, no interaction with geology.
2. Located on an ice-free area.
3. Very common rock type.
4. Built in a low coastal oasis.
5. Rock type/geological structure represented by <1% of Antarctica.
6. Located within 10 km of an area of significant geological value.
7. Within a geologically significant region.
8. Located within 1 km of an area of significant geological value.
9. Station built within a dry valley.
10. Station built upon an area of significant geological value.

Table 2. (*Continued*)

Biological Significance

1. Polar plateau bioregion, no bryophytes, lichen, bird or mammal species present.
2. Continental Antarctic bioregion, or presence of 1+ bryophytes or lichen species, 10+ terrestrial algae.
3. Regular presence of 1+ bird and/or mammal, or 5+ bryophytes, or 10+ lichen, or 50+ terrestrial algae.
4. Coastal Continental Antarctic bioregion.
5. Regular presence of 5+ bird and/or mammal, or 10+ bryophytes, or 20+ lichen, or 100+ terrestrial algae.
6. Maritime Antarctic bioregion, 10+ bird and/or mammal species regularly present.
7. 5+ bird and/or mammal species breeding/moulting in groups of 50+ per species, or 25+ bryophyte species.
8. 10+ bird and/or mammal species breeding/moulting in groups of 100+ per species, or 50+ bryophyte species.
9. Presence of 1+ vascular plant species, or 15+ bird and/or mammal species breeding/moulting.
10. Presence of 1+ vascular plant species, or 20+ bird and/or mammal species in groups of 100+ per species.

study, the applicability of the disturbance buffer was tested, the heavily modified surfaces mapping was ground-truthed, and further operational data and information were obtained. Access to Australia's Casey Station allowed for supplementary testing of the application of this study's footprint.

The original mapping of the heavily modified surfaces around Davis Station was produced solely from photography with an undetermined accuracy. During the field study at Davis, the accuracy of this mapping was tested. This was achieved by measuring the extent of heavily modified surfaces around the station area. The extent of modification to some specific station areas was difficult to determine solely from photography, so these locations were identified and measured. The partitioning of heavily modified surfaces at Davis, in relation to moderate and lightly modified surfaces, was at the author's discretion using the definition "natural surfaces that were disturbed to a similar extent to roads and other compacted, levelled, areas". All field measurements were then applied to the heavily modified surfaces map and amendments, where necessary, were applied.

The disturbance buffer's applicability was tested by identifying specific locations around the station where infrastructure was surrounded by an open, measurable and undeveloped environment. At these locations the visually-apparent extent of modified surfaces was measured at various points of the buildings and compared to the buffer distance applied to them. The buffer's accuracy for a range of infrastructure types was tested at 23 different locations at Casey and 16 at Davis Station. These points included newer and older buildings, piping, antennae, scientific instruments, tanks, and roads — encompassing the diversity of structures occurring around Antarctic research stations.

Results

The mapping of all areas of ground that appeared to be significantly modified and subject to traffic (roads, short-cuts, parking, garage and building access) cover a significantly larger area than the previously mapped AADC road footprint. Figure 1 illustrates the existing AADC road network overlaying the new heavily modified surfaces layer — showing a significant increase in road-like areas. The heavily modified surfaces footprint was 89 957 m^2 (8.9 ha), compared to a previous road area total of 24 525 m^2 (2.45 ha), a difference of 65 432 m^2 (6.5 ha). The addition of this more comprehensive heavily modified surfaces area (in comparison to the existing road area) has produced a significantly larger footprint than previously measured.

Fig. 1. Davis Station 1:3000 scale, illustrating the building footprint, heavily modified surfaces, and disturbance buffer, map produced by author using topographical data supplied by the Australian Antarctic Data Centre.

Davis' field huts buildings have a combined estimated area of 210.75 m^2. In context, the summer accommodation module (SAM) at Davis Station has an area of 283 m^2. With the five metre disturbance buffer applied to the field huts they produce a total environmental impact footprint of 2 175.6 m^2 (0.2 ha). These figures are approximated as there was limited data available for these field huts, and the disturbance surrounding these huts is very spread out and hard to assess remotely (B. Jones, pers. comm. 2/10/08).

Table 3. Potential format for station-comparison reporting.

Environmental Impact Footprint Report Station: Davis Station (Australia)
Total Footprint
Date Measured: 29 July 2008 (Field Assessed 11 December 08)
Location: 68°34.63'S 077°58.35'E
Total Footprint: 189,585.5 m^2
Station Footprint
Disturbance Footprint (Buffer): 99,628.82 m^2
Station Buildings Area: 13,185 m^2
Heavily Modified Surface Area: 89,956.74 m^2 (levelled and cleared glacial till)
Remnant Landfill Site: Yes — 1,500 m^2 (estimate)
Quarry: Yes — 3,000 m^2 (estimate)
Field Huts: 13 — 2,175.6 m^2 (including buffer area, floor area: 210.75 m^2)
Type of Building Designs:
63 Permanently foundered (12,558 m^2)
2 Semi-Permanent (412 m^2)
13 Temporary (215 m^2)
Location Characteristics
Station Construction: 8 — On-site foundations, significant anchoring.
Station Location: 7 — Area of significant scientific value, coastal, ice-free.
Geological Significance: 7 — Within a geologically significant region.
Biological Significance: 4 — Coastal continental Antarctica bioregion.
Environmental Domain: D
Antarctic Conservation Biogeographic Region: 7 (1,360 km^2)
Standardised Index
Footprint: 8,617 m^2/person (winter low: 22), 2,708 m^2/person (summer peak: 70)
Fuel Usage: 45.9/litres/person/day [568,714 litres (2007), 595,308 litres (4-year average)] Special Antarctic Blend)
Water Usage: 55/litres/person/day [687,900 litres (2007), 789,962 litres (4-year average)]
Wastewater Production: 49.9/litres/person/day [619,110 litres (2007), 710,966 (4-year average) (estimate)]

Of the 78 buildings at Davis, 65 have fixed foundations and 13 are portable. A total of 63 of the fixed buildings have cement foundations poured on site. The remaining two fixed buildings are the SAM using a majority-precast foundation, and the field store with a completely pre-cast foundation. The 13 portable buildings include steel shipping containers used for storage. The older poured-onsite foundation AANBUS (Australian Antarctic Building System) buildings contribute to 95% of the total building footprint at 12,557.5 m^2 (1.25 ha). The two newer precast buildings contribute 3% at 412.3 m^2. The remaining 13 portable buildings contribute to 2% of the total footprint with 215.15 m^2 of the building area.

The quarry's area of disturbance is approximately 5 015 m^2 (0.5 ha) and the landfill site is 4 185 m^2 (0.4 ha), however the depths or volumes were unavailable. The only information available for the landfill site was an estimated shape and its area.

The total area of disturbance, including the total area of all station infrastructure with the 10 metre, five metre, and one metre buffer areas applied was 189 585.5 m^2 (19.9 ha). This is illustrated in Map 1. By standardised index the station footprint for the summer maximum was 2 708 m^2/person and by winter minimum was 8617 m^2/person (winter average population of 22, peaking at 70 (COMNAP, 2009)). The heavily modified surfaces area prior to the field study was recorded as 65 973 m^2(6.6 ha), but was increased to 89 957 m^2 (8.9 ha) post field study (Fig. 1).

For the standardised index, fuel usage was 45.9 litres/person/day of diesel. Water usage was 55 litres/person/day, although due to the metering system, this figure may be greater. Wastewater production was an estimated figure of 49.9 litres/person/day. For the location descriptors Davis Station was placed at 8 for Station Construction, 7 for Station Location, 7 for Geological Significance, and 4 for Biological Significance (Table 3).

Discussion

The results of testing the disturbance buffer at Casey and Davis stations revealed that the disturbance was either accurate or in excess of the area applied by this model. Only two features revealed a disturbance area less than the buffer that was applied — cable piping and a building constructed in the 1960 s, which were then rectified. Table 1 illustrates the sites used in the field study, and the result from measuring the observed disturbance surrounding station facilities.

The majority of the disturbance test sites either matched or exceeded the buffer applied to them (Table 1). The buffer was particularly effective at Casey Station, where there is greater snow and ice cover concealing apparent disturbance in photography when compared to Davis. This demonstrates that the buffer distances used by this study should be treated as a minimum.

Significant increases of heavily modified surfaces were found while conducting the field study at Davis. Areas were found to be modified to a similar extent to roads, yet were not for regular vehicular access. These areas included significant temporary container storage, general material storage, and access routes. The increase in heavily modified areas detected after the field study demonstrated that 26.7% was not detected from the desktop inspection of aerial photography. This includes scope for the inclusion of moderate and lightly modified areas in future studies.

The preceding AAD SoE report footprint measurement for Davis was 37 709 m^2. When compared to the result produced by applying this model, 189 585 m^2, it demonstrated that this study found a significant difference in how "footprint" could be measured. This is why a standardised approach is so important if there is any attempt to compare various Antarctic stations.

The inclusion of field huts is an important, but easily overlooked, expansion of a station's footprint. Many Antarctic stations maintain field huts and refuges, the distribution of which spreads environmental disturbance into remote areas. It also decreases the wilderness values of the remote areas they are located within — an aspect discouraged by the Madrid Protocol's environmental principles. For the production of this study, limited data were available for the field huts from the AAD, which otherwise maintains a high degree of information for its assets in Antarctica. This shortfall of information may demonstrate that there is a lesser understanding of the larger-scale footprint spread out from stations and their field huts.

This model for measuring has gone beyond providing a measurement of the area of the environment impacted by the presence of operation of an Antarctic Station. To accurately portray the location that an Antarctic station occupies in a comparative context, the location descriptors have enabled an impartial depiction of the footprint of a station. The inclusion of these descriptors has been a novel invention. The descriptor table with peer-judgment assists these descriptors being appropriately applied. There is also the potential for the location descriptors to be combined with a station's footprint area in an algorithm that computes a comparative footprint area. Although consideration was given to this concept, the aim of this study was not to critique a large or small station footprint — which this may be perceived as doing.

Both the mapping and the numerical measurements from this study identified significant increases in the footprint area of the tested station. Although the mapping provides a good illustration of the actual footprint area of a station, it is the numerical result that enables comparison. By calculating the prescribed measurements a method has been developed that should enable accurate cross-comparison.

Conclusion

The problem that provoked the original conception of this study was the lack of knowledge of, or a consolidated approach to, the footprint of Antarctic stations by their operators. This study's aim was to address this by providing an environmental assessment tool for measuring station footprint in a way that enabled it to be applied to any station, and accurately represented the area on the ground that was physically affected by the station's presence. This would then give a station's environmental manager a clear measurement of the existing environmental impact, and how it compared to others. The intention was not to produce a definitive study, but predominately to provoke, and to provide a platform for, the usage of environmental footprints for stations amongst national Antarctic programs and the ATS. In addition to providing a tool for Antarctic environmental assessment, the resultant product of this study could be modified for use elsewhere in the world.

In practice, the application of this model to other stations throughout Antarctica may be challenging. Throughout the development of this study, access to very accurate GIS information, aerial photography, and fieldwork on the test case station was available. Access to this amount of information may not, however, be available for all other stations. Of the 81 Antarctic stations (COMNAP, 2009) GIS quality maps were found for only three stations (Zhong Shan, Progress 2, Palmer) and orthophotographic images were found for only a further three stations (McMurdo, Rothera, Amundsen-Scott South Pole Base). The extent of the retention of this information that is not publically available was unknown. Having these data available significantly increased the level of accuracy possible. However, not having these data does not excuse the inability to measure a station's footprint. With access to high-resolution satellite imagery an accurate estimate of most Antarctic stations would be possible. It is this exact lack of information that highlights the problem that prompted this study. If national operators do not have mapping or an estimate of their station's footprint on the Antarctic environment, and how it relates to other stations, is it not possible to fully appreciate the extent of their environmental impacts, and therefore conformity with the Madrid Protocol.

The parameters that were included for measuring footprint in the model produced by this study, although intended to be applicable to any station, were formulated with data that were predominantly from Australia's stations. The feature that could vary between environments and operators would be the assumed disturbance buffer. This buffer, however, was tested at two Antarctic stations with distinct environments and was found to be effective. These were all found to be accurate to, or underestimating, the actual disturbance surrounding facilities. A significantly different method of station construction or usage could, however, vary the actual disturbance area — requiring modifications to the buffers applied. A reduction in the buffer area for other stations to less than those applied in this study would require justification. The location descriptors and the standardised index, although amenable to refinement, are intended to be universally applicable.

The adaptation of this footprint model to environments outside Antarctica would require some key considerations. As a prerequisite its application would need to be within locations that have similarly confined environmental impacts. The foremost modification required would be the development of location descriptors to suit the target environment. Alteration of other features, such as the buffer areas, would also require consideration to address the type of industry or infrastructure being assessed. Foreseeable applications of this footprint outside Antarctica could include extractive and research facilities in remote areas of the Arctic, or tourism developments within otherwise wilderness locations. The benefits of the usage of this environmental footprint to such industries would be similar to those provided in the Antarctic context, including comparability, an assessment of pre-existing environmental disturbance, and a tangible quantification for environmental managers.

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